2 - 7 September 2007

IRMMW - THz 2007 Cardiff

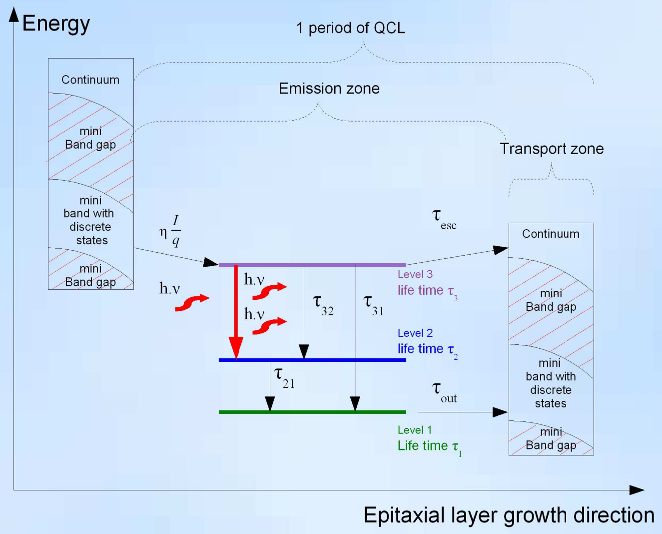
THE JOINT 32ND INTERNATIONAL CONFERENCE ON INFRARED AND MILLIMETRE WAVES AND THE 15TH INTERNATIONAL CONFERENCE ON TERAHERTZ ELECTRONICS

SUPAERO

Modeling of static and dynamic behavior of 2.9 THz Quantum Cascade Lasers.

M.O.S.E.
Micro-ondes et Optoelectronique pour Systèmes Embarqués*

Abstract : Quantum Cascade Laser are at the same point of development nowadays than were the first semiconductor lasers in the 1960's. Indeed it still needs to be cooled at cryogenic temperatures (between 4K and 70K for our 2.9 THz QCL, even though some could be used at room temperature with decreased output power



Rate equations of a Quantum Cascade Laser

$$\frac{\partial N_3}{\partial t}=\eta.\frac{I}{q}-\frac{N_3}{\tau_3}-G.(N_3-N_2).S$$

$$\frac{\partial N_2}{\partial t}=\frac{N_3}{\tau_{32}}-\frac{N_2}{\tau_{21}}+G.(N_3-N_2).S$$

$$\frac{\partial N_1}{\partial t}=\frac{N_3}{\tau_{31}}+\frac{N_2}{\tau_{21}}-\frac{N_1}{\tau_{out}}$$

$$\frac{\partial S}{\partial t}=N_p.G.(N_3-N_2).S-\frac{S}{\tau_s}+\beta.\frac{N_3}{\tau_{sp}}$$

Static behavior

- P(I) curves at different temperatures
- Threshold current versus temperature variations
- Comparison with experimental curves

Dynamic behavior

- Small-signal frequency response
- Transfer function
- Bandwidth evaluation
- Variations of the transfer function with bias intensity and temperature

Optical gain G : $G=\Gamma.\sigma.\frac{c}{n}$

with : - Optical confinement $\Gamma = 0.27$
- Optical linear gain $\sigma = 1.6\text{e-9 cm}$
- Light velocity $c = 3\text{e8 m/s}$
- Refractive index $n = 3.3$

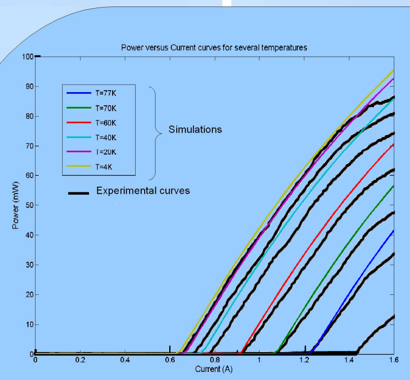
Invert of photon life time : $\frac{1}{\tau_s}=\alpha\frac{c}{n}=(\alpha_i+\alpha_m).\frac{c}{n}$

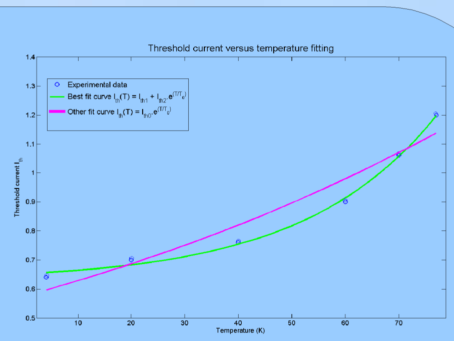
with : - mirror losses $\alpha_m=\frac{1}{2L}\ln\left(\frac{1}{R_1.R_2}\right)$

- internal losses $\alpha_i = 20\ cm^{-1}$

Others life times :
$\tau_{21} = 0.3\ ps$
$\tau_{31} = 1.3\ ps$
$\tau_{32} = 2.4\ ps$
$\tau_{sp} = 7.0\ ns$
$\tau_{out} = 0.5\ ps$

Spontaneous Emission factor $\beta = 1e\text{-}4$
Current injection efficiency $\eta = 0.9$
Number of periods $Np = 90$
Cavity length $L = 3\ mm$
Cavity width $w = 200\ \mu m$





In order to fit the variations of the threshold current with temperature, it is common to use the expression :

$$I_{th}(T)=I_{th_1}+I_{th_2}.\exp\left(\frac{T}{T_0}\right)$$

It performs much better result than the well known law :

$$I_{th}(T)=I_{th_0}.\exp\left(\frac{T}{T_0}\right)$$

With the first relation, Matlab can optimize the different coefficients so that we obtain :

$I_{th_1}\approx 0{,}63\,A$ $\quad I_{th_2}\approx 25\,mA$ $\quad T_0\approx 25\,K$

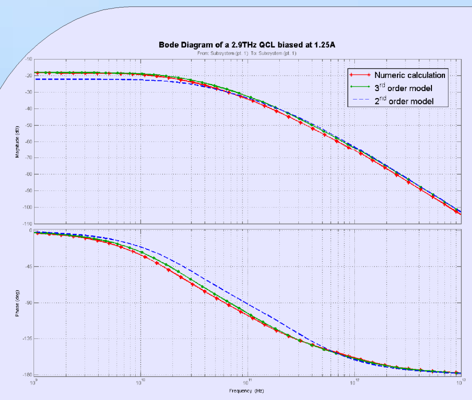
These values are in great agreement with some we can read in articles

The threshold current can be related to the optical gain as

$$I_{th}=\frac{\alpha}{N_p.g} \quad with \quad g=\tau_3\left(1-\frac{\tau_{21}}{\tau_{32}}\right).\frac{1}{q.\frac{c}{n}}.G$$

That leads to :

$$G(T)=\frac{G_0}{1+\gamma.\exp\frac{T}{T_0}} \quad with \quad G_0=\Gamma.\sigma.\frac{c}{n} \quad and \quad \gamma\approx 0{,}04$$

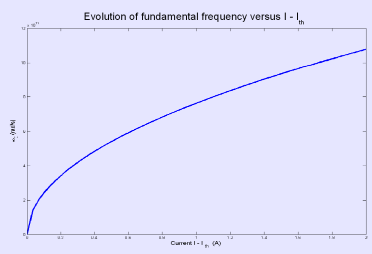


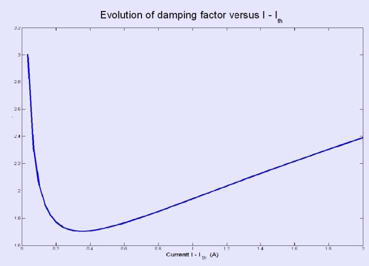
$$H(p)=\frac{H_0}{1+2\frac{\xi}{\omega_0}p+\left(\frac{p}{\omega_0}\right)^2}$$

with $\omega_0=\sqrt{\frac{2.G.S_0}{\tau_s}}$

leads to $f_{3dB}\approx\frac{\sqrt{3}.\omega_0}{2\pi}\approx 160\,GHz$

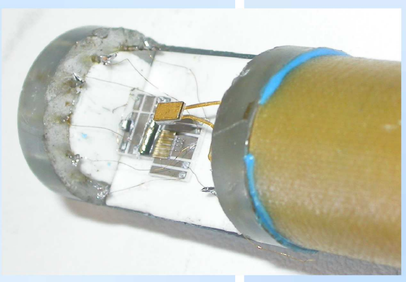
→ Great potential for free space high speed digital transmission

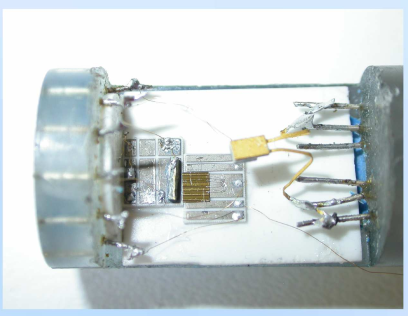


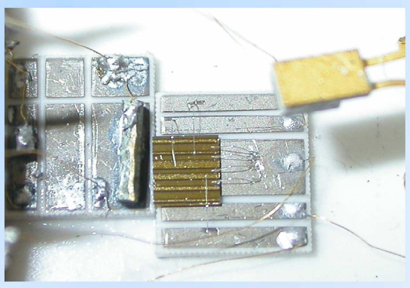


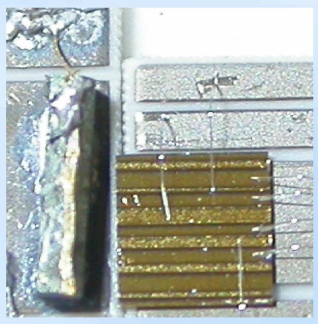
Modeling of this 2.9THz QCL by a non-resonant 2nd order transfer function system seems to lead to good results, in agreement with other research. Evolution of duping factor with bias current show that this QCL is always non-resonant

ω0 increases as the square root of the bias current, result well known for Fabry Perot semiconductor edge emitting laser.









SUPAERO / ENSAE : École Nationale Supérieure de l'Aéronautique et de l'Espace - 10 Avenue Edouard Belin BP 54032 - 31055 TOULOUSE CEDEX 04 - FRANCE

* MOSE : Micro-ondes et Optoelectronique pour Systèmes embarqués (Microwaves and Optoelectronic for Embedded Systems)